(a) Previous theory (b) Revised theory

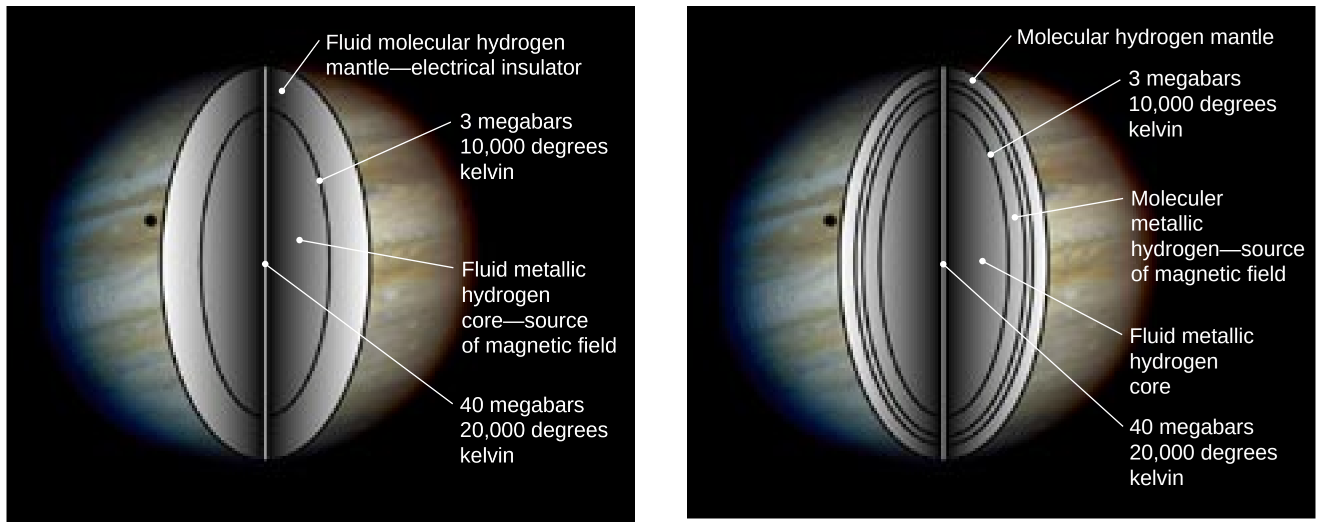

Figure 5. Our work has allowed us to calculate the electrical conductivity in the outer region of Jupiter. The planet's magnetic field is caused by convective dynamo motion of electrically conducting metallic hydrogen. Our results indicate that in Jupiter, the magnetic field is produced much closer to the planet's surface (b) than was thought previously (a).

stockpile stewardship research that will eventually be performed on NIF.

Future experiments will focus on (1) using various hydrogen isotopes—molecular hydrogen, deuterium, and hydrogen–deuterium—to determine the temperature dependence of the electronic energy gap, (2) exploring higher pressures up to 3 Mbar, and (3) probing effects in similar liquids such as molecular nitrogen and argon.

Key Words: gas gun; hydrogen—fluid, liquid, metallic; Jupiter; National Ignition Facility; shock compression tests; stockpile stewardship.

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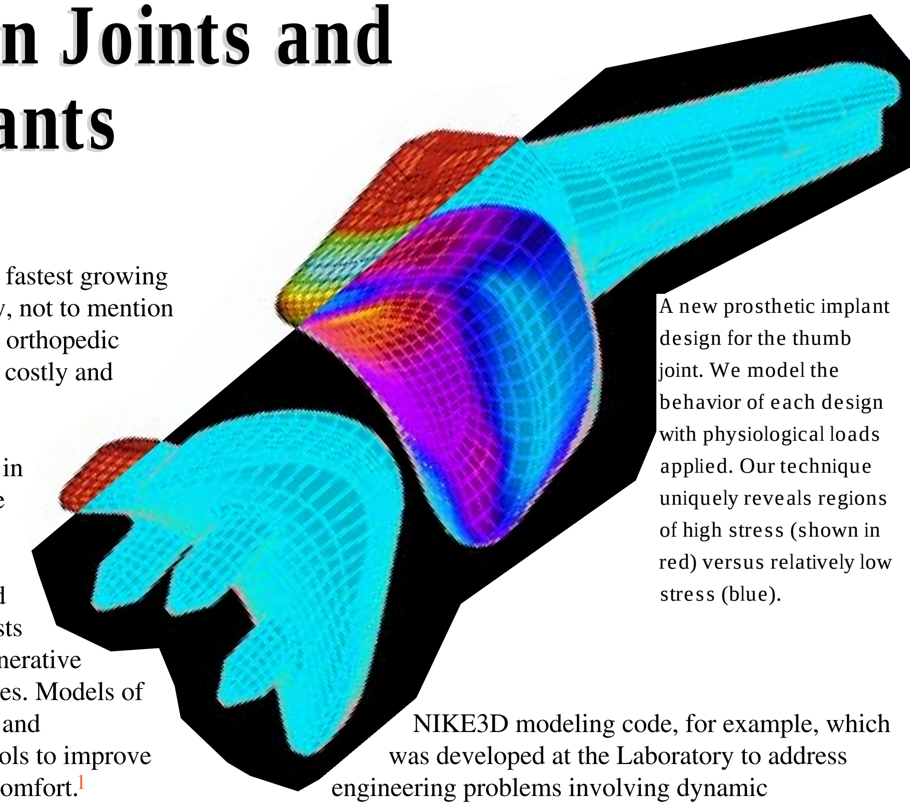
About the Scientist

Physicist WILLIAM NELLIS joined the Laboratory in 1973. His specialty is the investigation of condensed matter both during and after high-pressure shock compression. The highlight of this work is the observation of the metallization of fluid hydrogen at 1.4 megabars pressure and nine-fold compression. He has delivered invited talks at 44 professional conferences since 1979 and is the author or co-author of more than 100 papers. A fellow of the American Physical Society's Division of Condensed Matter Physics, Nellis holds M.S. and Ph.D. degrees in physics from Iowa State University. He received his B.S. in physics from Loyola University of Chicago.

Modeling Human Joints and Prosthetic Implants



A new prosthetic implant design for the thumb joint. We model the behavior of each design with physiological loads applied. Our technique uniquely reveals regions of high stress (shown in red) versus relatively low stress (blue).

REPETITIVE motion injuries are one of the fastest growing causes of lost time to business and industry, not to mention their impact on worker health and morale. The orthopedic surgery these injuries sometimes necessitate is costly and painful. The therapy and orthopedic implants associated with degenerative bone and muscle diseases and acute injuries are also costly, and in the case of implants, the initial cost may not be the final cost if and when the implant needs to be replaced.

Computational models of joint anatomy and function can help doctors and physical therapists understand trauma from repetitive stress, degenerative diseases such as osteoarthritis, and acute injuries. Models of prosthetic joint implants can provide surgeons and biomechanical engineers with the analytical tools to improve the life-span of implants and increase patient comfort.[1]

With such purposes in mind, the Laboratory embarked about three years ago on a mission to model the whole human hand at high resolution. The challenge is that most biological structures are dauntingly complex, and the hand is no exception. The human wrist alone has eight bones, and the rest of the hand has 19 more, to say nothing of soft tissues—ligaments, tendons, muscles, and nerves—and the interactions among them.

More recently, the Laboratory's Computational Biomechanics Group within the Institute for Scientific Computing Research (ISCR) narrowed the mission to a computational model focusing on the dynamics of specific bones and joints that are often associated with injury or damage. The group also undertook a closely related endeavor: creating a computational model of prosthetic joint implants, initially for the thumb.

In light of the complexity of these models and the need for very high accuracy, it is appropriate that a facility like LLNL—which offers powerful computational resources, an understanding of complex engineering systems, and multidisciplinary expertise—take on these tasks. It is also significant that the work is being done collaboratively through the ISCR and draws on experts from the Laboratory (particularly the Mechanical Engineering Department), academia, medicine, and industry (see the box on p. 20). The NIKE3D modeling code, for example, which was developed at the Laboratory to address engineering problems involving dynamic deformations, such as the response of bridges to large earthquakes,[2] is now being used as part of our collaborative joint modeling work.

Each person's bones differ in shape and size. Our models are based on the detailed anatomy of individual people. We start with high-resolution data obtained from computed tomography or magnetic resonance imaging, as shown in the illustrations on pp. 20–21. Images from a single hand scan involve several gigabytes of raw data, and the models developed from them are highly complex—thus the need for powerful computers.

Focusing on the Hand and Knee

We focused our initial attention on a few joints in the hand. One joint of considerable clinical interest is the thumb carpo-metacarpal (CMC) joint, which connects the long bone at the base of the thumb with the wrist. During routine grasping activities, CMC joint surfaces are subjected to total forces greater than 200 kilograms (440 pounds), so it is not surprising that injuries are common. The thumb is also often involved in repetitive motion injuries, and the CMC joint is the structure most affected in osteoarthritis, which strikes 8% of the U.S. population. Other joints of considerable interest are the knee and the proximal interphalangeal joint and the metacarpo-phalangeal joint in the index finger, which have some of the strongest ligaments in the hand.

Previous analyses of joint function (for example, rigid-body kinematic analyses) have typically provided less information than is possible through finite-element methods. On the other hand, most finite-element analyses of biological systems have been linear and two dimensional. We are applying three-dimensional, nonlinear, finite-element codes that assign material properties to bone and the soft-tissue structures associated with joints.

For example, using the NIKE3D modeling code to look at biological problems for the first time, we can model bones as materials that are more rigid than tendons, but less rigid than a metal implant. Soft tissues are inhomogeneous, undergo deformation, and some show elastic behavior. Our methods simulate tissue behavior under various loads, and joint movement with and without prosthetic implants, and they can assess injury following trauma, such as that caused by a car crash. Because we can assign different material properties to the tissues and examine a range of loads that are experienced in real life, our methods allow us to see interactions between tissue types for the first time, and we can identify regions of high stress. Our high-quality visualizations, such as the one shown in the illustration on p. 19, display complex results in easy-to-understand form.

Two main issues are the computer time needed to run a finite-element code and the labor needed to develop a model from each new scanned data set. We are addressing the first problem by working on powerful supercomputers and by preliminary research in partitioning biological finite-element models to run on massively parallel machines.[3] To address the second problem, we are automating as much of the modeling process as possible.

Collaborators in Biomechanics Modeling

ISCR biomechanics research is collaborative in the broadest sense. At Livermore, we work with experts in computer vision, mechanical and electrical engineering, nondestructive evaluation, health care technology, health services, and with visiting scholars and students. Partners outside the Laboratory include:

Academic institutions
University of California, Berkeley
University of California, San Francisco
University of California, Davis
University of California, Santa Cruz
University of New Mexico
Institute for Math and Computer Science, Hamburg, Germany

Medical facilities
Kaiser Permanente
G. W. Long Hansen’s Disease Center
Louisiana State University Medical Center
Massachusetts General Hospital
Children’s Hospital, San Diego

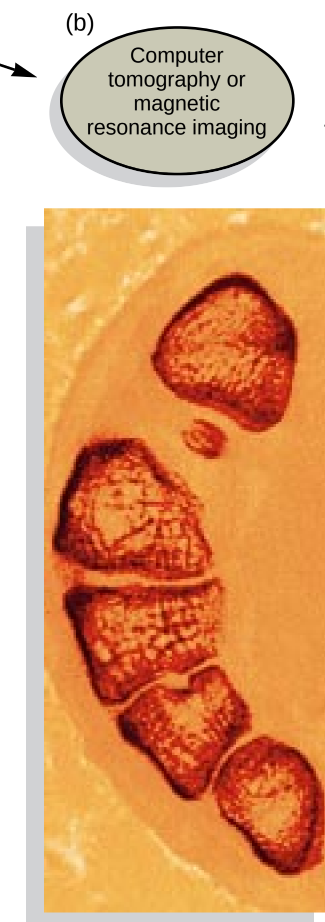
Industry
ArthroMotion/Avanta Orthopedics, Inc.
ExacTech
Orthopedic Biomechanics Institute
National Highway Traffic Safety Administration
Wright Medical, Inc.
XYZ Scientific Applications, Inc.
Zimmer, Inc.

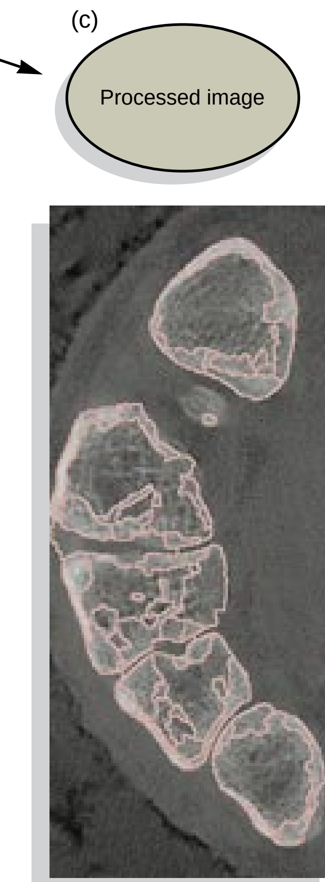
Other 3D Visualization Tools

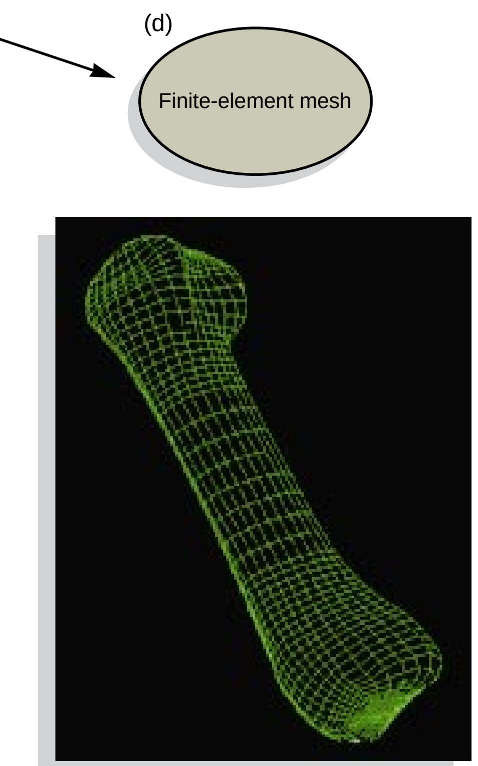
We are also designing three-dimensional computational tools to interactively move tissues so we can simulate surgical procedures. In the future, we plan to extend our modeling to include additional joints and perhaps internal organs, such as the heart, lungs, and liver.

How can our computational tool benefit the clinical community and ordinary individuals? Our models provide data on internal joint stresses and strains that are not otherwise obtainable. They can be used by surgeons to help plan treatment and to assess outcome following a traumatic or repetitive motion injury. They can help a surgeon predict results, such as strength, range of motion, and other indicators of function after an operation.

Orthopedic implants are a multibillion-dollar U.S. and worldwide industry; however, today’s prosthetic joint implants have high failure rates. They often loosen, wear, and fail before the end of a recipient’s life, necessitating painful and costly replacement. Orthopedic implants last on average







Starting with (a) an individual human hand, we obtain (b) raw magnetic resonance imaging or computed tomography scans. The scan shown here is a cross section of bones and surrounding tissues proximal to the knuckles. From many cross sections, we (c) process the images and then generate (d) a high-quality, three-dimensional mesh that is suitable for finite-element analysis.

5 to 15 years. The initial implant can cost about $20,000; revision implants are more expensive. Our methods can eventually be applied to any human joint for which prosthetic implants have been designed. Our models are leading to better designs for prosthetic implants, resulting in longer life spans and fewer costly followup operations. Finally, our work can help the automobile industry to develop safety features that will protect against injury to the head, chest, and lower extremities.

Key Words: biomechanical modeling, finite-element modeling, Institute for Scientific Computing Research (ISCR), NIKE3D, prosthetic point implants.

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2. *Energy & Technology Review*, UCRL-52000-95-9/10 (September/October 1995) is devoted to a series of articles on computational mechanical modeling, including NIKE3D.
3. For more information on finite-element modeling using massively parallel processors, see “Frontiers of Research in Advanced Computations,” *Science & Technology Review*, UCRL-52000-96-7 (July 1996), pp. 4–11.

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